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Key Points:
- A slow spread of deformation is initiated by one earthquake and triggers others
- The African subduction and the North Anatolian Fault are mechanically coupled
- Slow deformation spreads to far distances and lasts for several years

Supporting Information:
- Readme
- Text S1
- Table S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7
- Figure S8

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Observation of the spread of slow deformation in Greece following the breakup of the slab

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Abstract Over the past two decades, geophysical observations have shown that earthquakes can trigger other earthquakes, raising the possibility that earthquake interaction plays an important role in the earth's deformation. We analyze here a "storm" of earthquakes in Greece and show that their interaction provides remarkable insight into the mechanics of one of the fastest deforming continental region in the world. A rupture of the African slab initiates a cascade of large earthquakes and a long episode of slow slip marking the downward plunge of the slab, the concomitant rollback of the subduction, and the subsequent detachment of southern Greece from the Eurasian plate. Intense crustal deformation, indicative of the resulting plate stretching, follows. This slow deformation which spreads in a few months over more than 500 km lasts ~3 years and triggers earthquakes. The observations also show that the retreat of the African subduction is the motor of the Aegean deformation.

1. Introduction

The geodynamics of Greece results from the interaction between three plates and involves a wide variety of tectonic processes. Although data and measurements have been accumulated over the years, the underlying processes of its deformation are still debated [*Le Pichon and Kreemer*, 2010; *Shaw and Jackson*, 2010; *Reilinger et al.*, 2010; *Floyd et al.*, 2010; *Brun and Sokoutis*, 2010; *Pérouse et al.*, 2012; *Jolivet et al.*, 2013; *Paul et al.*, 2014]. To the south and southwest, Greece is surrounded by the Hellenic trench which marks the beginning of the plunge of the African plate under Aegean-Anatolia [*Papazachos and Comminakis*, 1971] (Figure 1). Entering from the northeast, the North Anatolian Fault (NAF), which marks the boundary between the Eurasian plate and the Aegean-Anatolian domain, crosses the North Aegean Sea and reaches the Corinth Gulf in central Greece [*Armijo et al.*, 1999] (Figure 1). Aegean crustal tectonics and seismicity is dominated by N-S extension [*Taymaz et al.*, 1991; *Hatzfeld et al.*, 1999; *Briole et al.*, 2000; *Kiratzi and Louvari*, 2003; *Bernard et al.*, 2006] attributed to the southward rollback of the African subduction [*McKenzie*, 1978; *Le Pichon and Angelier*, 1979].

2. The Breakup, Plunge, and Rollback of the African Slab

In 2008, an unusual number of large earthquakes [*Papadimitriou et al.*, 2008; *Papadopoulos et al.*, 2009] (Figure 2, supporting information Figure S1) occurred in Greece. During the first half of the year, five M ≥ 6 earthquakes shook the area displayed in Figure 2, more than had occurred in the previous 10 years.

The sequence of events begins on 6 January with the Mw 6.2 Leonidio earthquake, located ~80 km below eastern Peloponnese (Figure 2b, #1). Its mechanism shows that it corresponds to the rupture of a low-dipping plane with the top block moving nearly horizontally (dip 3°) SSW (strike N209°) toward the trench [*Zahradnik et al.*, 2008; *Kiratzi and Benetatos*, 2008] (Figure 1). This mechanism attributed to downdip tension within the slab [*Kiratzi and Papazachos*, 1995] and indicative of intra-slab rupture along a sub-horizontal plane is now recognized to be the dominant mechanism of intermediate-depth earthquakes in subduction zones [*Kiser et al.*, 2011]. Interestingly, the slip direction inferred is precisely the direction of plate motion there inferred from GPS [*Reilinger et al.*, 2010; *Pérouse et al.*, 2012]. The Leonidio earthquake was only the second M ≥ 6 earthquake deeper than 50 km in the Hellenic subduction in 10 years. Two years before, the Mw 6.7 Kythira earthquake had

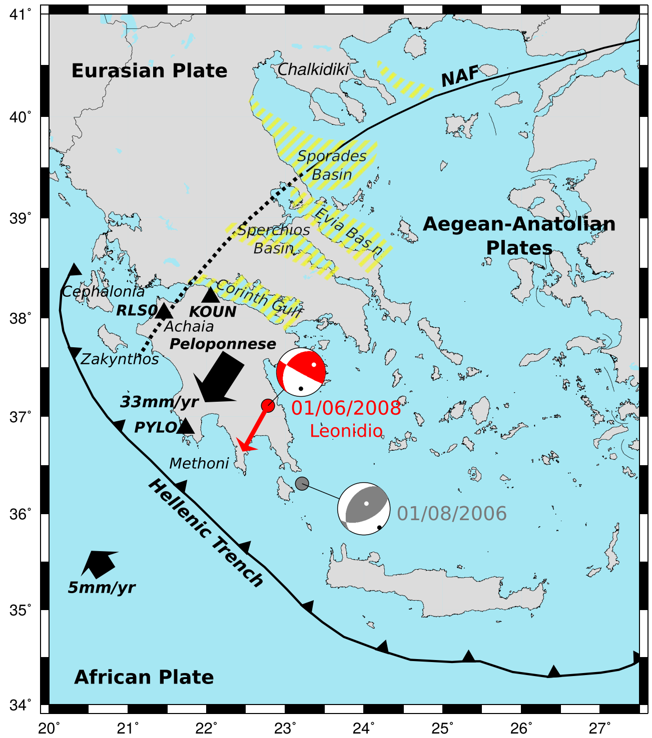

Figure 1. Map showing the three tectonic regimes in Greece: The Hellenic Trench (solid line with triangles pointing to the plunging slab), the North Anatolian Fault (NAF, solid line) and its schematic hypothetical prolongation (dotted line) represented by the envelope of the large GPS velocity vectors of Aegean [*Reilinger et al.*, 2006], and the major extensional basins [*Armijo et al.*, 1996, 1999] (yellow stripes). The black arrows show the motion of Peloponnese [*Reilinger et al.*, 2010] and Africa [*Pérouse et al.*, 2012] relative to Eurasia. The Peloponnese arrow is also the direction of absolute plate motion [*Pérouse et al.*, 2012]. The beach balls represent the mechanisms of the two M ≥ 6 intermediate-depth earthquakes in 10 years (1998–2008) with their P and T axes. The red arrow shows the movement of the top block during the January 2008 earthquake [*Zahradnik et al.*, 2008]. Triangles give the location of the GPS stations.

occurred further south (Figure 1) with a mechanism of arc-parallel compression [*Konstantinou et al.*, 2006], common for sub-crustal events in this subduction [*Hatzfeld et al.*, 1993; *Kiratzi and Louvari*, 2003], and indicative of arc-parallel contraction, resulting from the convex shape of the subduction. This event was not followed by anomalous seismic activation.

Within days of the slab rupture, the shallow part of the subduction, near the trench and updip from the rupture, becomes seismically active (supporting information Figure S3a). The large width of the zone activated (~100 km) indicates that a broad deformation of the shallow subduction area is taking place. This deformation, imaged by seismicity, develops for several weeks, accelerates on 13 February, and culminates on 14 February in the M_w 6.8 Methoni earthquake (Figure 2b, #2). This earthquake ruptures a NW-SE (~N300°) low-angle (~15°) thrust fault dipping landward [*Roumelioti et al.*, 2009]. It is the only M ≥ 6 event in this zone in 10 years. A second earthquake (Mw 6.5) with similar mechanism follows 2 h later (Figure 2b, #3). The depth of these events (~30 km) places them near the slab interface inferred from tomographic imaging [*Pearce et al.*, 2012], and their mechanism indicates that the slab is plunging. The connection between an intermediate-depth earthquake which breaks the slab (the January event) and a subduction earthquake which follows along the shallow slab interface above (the February 14 events) has been documented for a few events [*Dmowska et al.*, 1988]. In Greece, the short interval between the two types of earthquakes, compared to the few years usually reported, suggests that the January displacement of the upper part of the slab away from the overriding plate unclamped the plate contact and facilitated the downward slip of the slab.

On 20 February, a third large shock (Mw 6.2) hits this area (Figure 2b, #4). Its shallower depth (~10 km) places it in the overriding plate, directly above the 14 February rupture [*Roumelioti et al.*, 2009]. Its strike-slip mechanism is consistent with the partitioning of the plate convergence [*Reilinger et al.*, 2006; *Roumelioti et al.*, 2009]: The oblique motion of the African plate relatively to Aegean (Figure 1) is accommodated by their relative displacement perpendicular to the trench (and downward, the 14 February earthquakes) and parallel to the trench (and horizontal, the 20 February earthquake).

A GPS station close to the subduction (PYLO, https://gpscope.dt.insu.cnrs.fr/chantiers/corinthe; Figure 1) shows that the deformation of the shallow subduction continues for ~3 years (Figure 3b, supporting information Figure S4), during which southwestern Peloponnese moves slowly southward relatively to the rest of Greece. Another station ~150 km away (KOUN, Figure 1, supporting information Figure S5) shows that this slow deformation extends to northern Peloponnese, which moves faster southward in the ~3 years after these earthquakes than before.

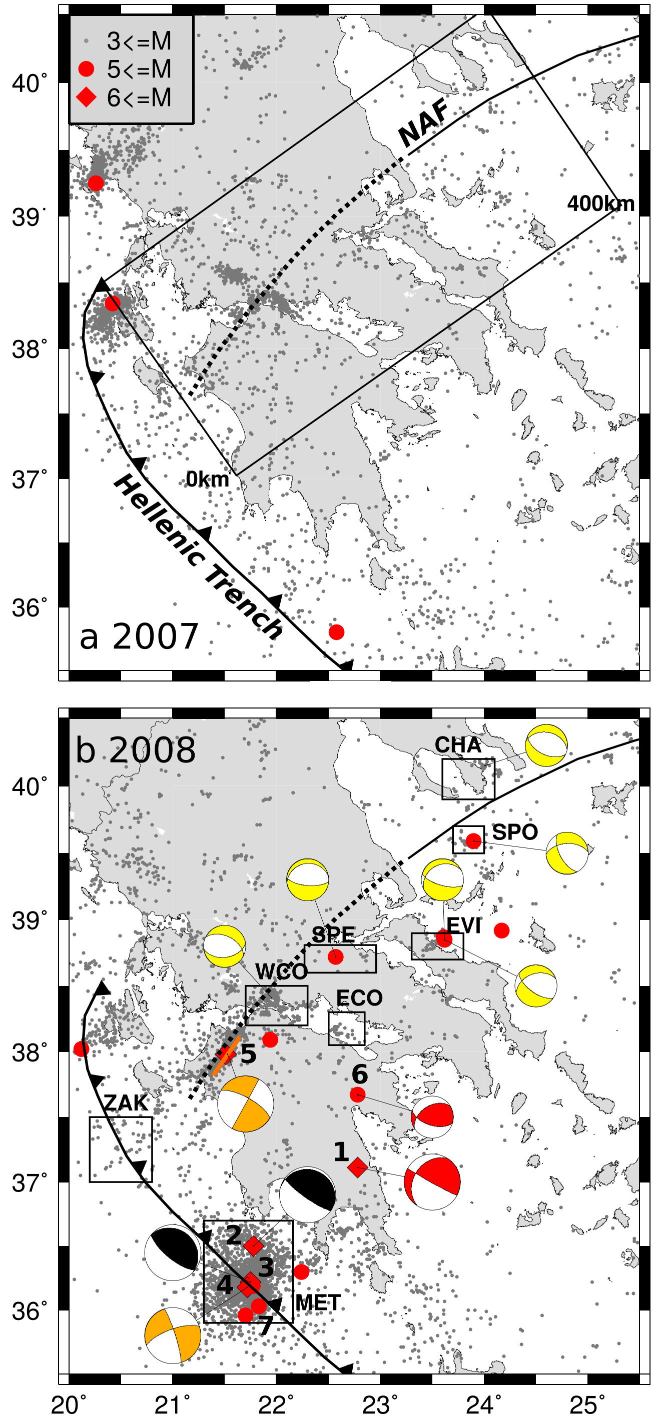

Figure 2. Seismicity in (a) 2007 and (b) 2008 (from the Observatory of Athens catalog) and mechanisms of the events discussed [*Zahradnik et al.*, 2008; *Roumelioti et al.*, 2009; www.geophysics.geol.uoa.gr] (red = intra-slab rupture at intermediate-depth; black = subduction earthquakes; orange = strike-slip earthquakes; yellow = extensional earthquakes). The rectangle in Figure 2a outlines the region in supporting information Figure S1. Boxes in Figure 2b show the areas considered in Figure 3a and supporting information Figure S7: MET: Methoni, ZAK: Zakynthos, WCO: West Corinth, ECO: East Corinth, SPE: Sperchios, EVI: Evia, SPO: Sporades, CHA: Chalkidiki. The orange line is the Achaia rupture. Numbers show the chronology of the Peloponnese earthquakes.

The mechanical behavior depicted—the unclamping of the slab away from Aegean, the concomitant seismic and aseismic slip at shallow depth in the subduction, the broad deformation zone developing near the trench, and the slow southward motion of Peloponnese—seem to logically describe the concomitant rollback and plunge of the slab and the spread of the associated deformation.

3. The Slow Spread of Deformation

On 8 June, while the subduction continues to deform slowly, the largest strike-slip earthquake in continental Greece in 25 years, the Mw 6.4 Achaia-Elia earthquake, hits northwestern Peloponnese (Figure 2b, #5). Its ~25 km long strike-slip rupture [*Margaris et al.*, 2010] lies in direct continuation of the North Anatolian Fault zone (Figure 2b). Its link with the deformation of the subduction is supported by the early aftershock pattern of the February earthquakes (supporting information Figure S3b) which shows, besides the expected epicentral patch, the activation of a linear feature, lying in the prolongation of the NAF and linking the June rupture to the subduction. Activation of this feature, which displays the same mechanism as the June rupture, begins near the trench, a few hours after the Methoni earthquake. A GPS station a few kilometers north of the Achaia rupture (RLSO, Figure 1, supporting information Figure S6) shows that the area was pulled ~2 mm southward in February by the Methoni earthquake. The northward elastic rebound of the station during the June earthquake thus logically appears as the partial detachment of southward moving Peloponnese from the stable Eurasian plate along a boundary in direct prolongation to the NAF.

Ten days later, on 18 June, a M 5 intermediate-depth earthquake occurs under northeastern Peloponnese (Figure 2b, #6). Then on

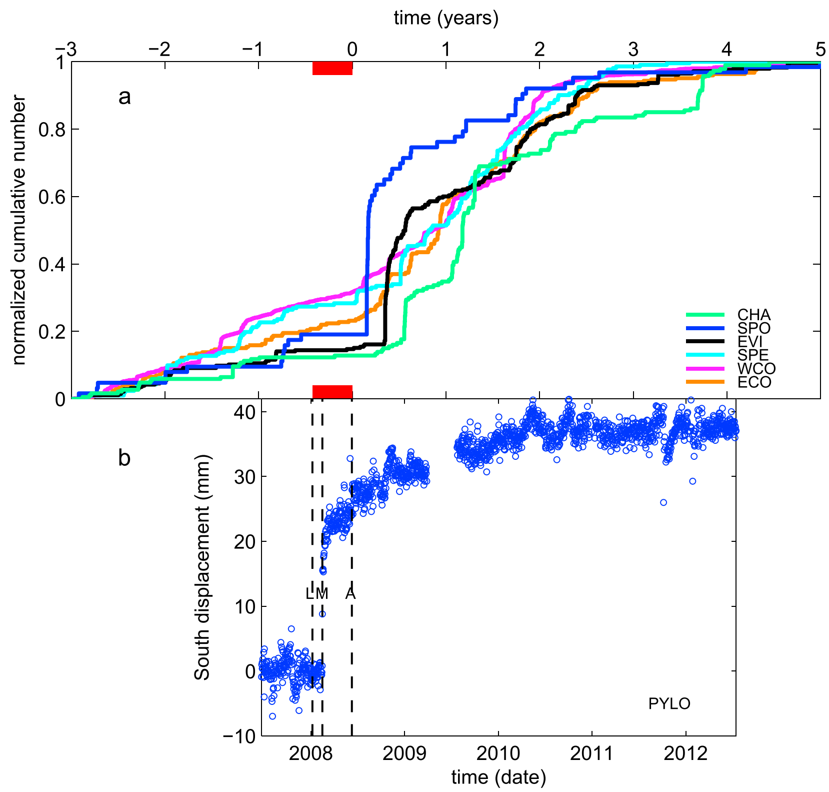

Figure 3. Time comparison between the evolution of seismicity in the extensional basins of Greece and the displacement of SW Peloponnese. (a) Evolution of the cumulative number of events in the major seismic extensional clusters (shown in Figure 2b). Time is measured from the occurrence of the Achaia earthquake, which ends the period of M ≥ 6 earthquakes shown by the red band. Each curve is normalized to its final value. (b) Southern displacement of GPS station PYLO (Figure 1), corrected for interseismic velocity and seasonal variations. Dashed lines indicate occurrence times of (L)eonidio, (M)ethoni, and (A)chaia earthquakes.

21 June, a M 5.6 earthquake takes place on the Peloponnese segment of the Hellenic trench (Figures 2b, #7). After June, no M ≥ 5 earthquake occurs in Peloponnese until year end, but by then seismic activity has been intense for 6 months throughout southern Greece (Figure 4a). In the second half of 2008, the deformation spreads to central and northern Greece (Figure 4b).

Within a few months of the Peloponnese earthquake storm, seismicity in all the major extensional basins of Greece increases (Figure 3a). This activation will last for ~3 years, a duration similar to the slow motion of Peloponnese (Figure 3b) following the subduction earthquakes. It is accompanied by an unusual number of M ≥ 5 earthquakes (5 in 2008 alone) whose mechanism (www.geophysics.geol.uoa.gr; Figure 2b)—normal faulting on east-west trending planes—represents the brittle response of the upper crust to N-S extension (stretching). The delay between the southward motion of Peloponnese and the onset of activation in central and northern Greece logically represents the time for strain to be transferred through the viscous upper mantle.

4. Discussion and Conclusions

The 2008 sequence of earthquakes shows that an intermediate-depth rupture of the slab initiates a process (or is its first recognizable stage) that sees the upper part of the slab move SSW (away from Aegean), the African plate plunge, Peloponnese move to the south, and crustal extension spread to central and northeastern Greece. One notable aspect of this cascade of earthquakes is that the mechanics it depicts is close to the one which has long been thought to guide and control the deformation of the region [*McKenzie*, 1978; *Le Pichon and Angelier*, 1979]. It shows that the rollback of the subduction, associated here with the deep breakup of the slab, is the motor of the Aegean deformation. It also shows the existence of coupling

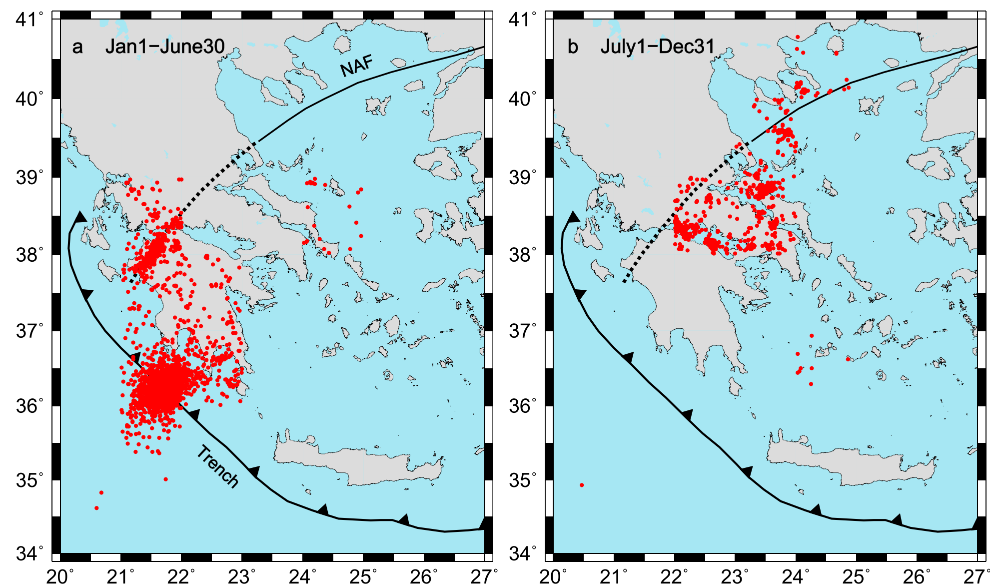

Figure 4. Spread of the deformation in Greece following the slab breakup. (a) Seismicity in the first half of 2008 in areas where the cumulated seismic moment during this period is more than 10 times its corresponding value of previous years (2003–2007). (b) Same as Figure 4a for the second half of 2008.

between the subduction and the prolongation of the NAF, suggesting that the North Anatolian Fault zone extends to the subduction. Its curved geometry suggests its past capture by the subduction. In turn, this geometry, which parallels the GPS and seismic slip vectors, seems to be now what guides the kinematics of the region at the lithospheric scale. In this view, the ~100 km wide zone of strike-slip motions extending from Cephalonia Island to Achaia [*Shaw and Jackson*, 2010] is the result of the convergence of two parallel faults, one—the Cephalonia transform—born in the subduction itself as it separates the northern continental lithosphereric segment from the southern oceanic one, the other—the NAF—having penetrated the Aegean from the northeast.

The observations also show that small seismicity is a remarkably sensitive tool to map slow deformation, and its combination with GPS data is most valuable. The intriguing observation that slow deformation can spread over more than 500 km in a few months, and trigger earthquakes this far, months or years later helps understand why some large earthquakes cluster in space and time or why some faults rupture in a succession of earthquakes which occur months or years apart.

Acknowledgments

The seismic data are available on the website of the National Observatory of Athens at the following address: http://www.gein.noa.gr/en/seismicity/earthquake-catalogs. Data from 2005 are used in this article. The earthquake mechanisms can be found on the Department of Geophysics of the University of Athens website: http://dggsl.geol.uoa.gr/en_index.htmlHYPERLINK. We are very grateful to Pierre Briole and Olivier Charade for providing the raw GPS data of PYLO and KOUN. We thank the scientists and staff of the National Observatory of Athens who make the earthquake catalog and those of the Department of Geophysics of the University of Athens who provide some of the mechanisms.

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